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Dependence of Explicit and Implicit Memory on Hypnotic State in Trauma Patients

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Background: It is still unclear whether memory of intraoperative events results entirely from moments of inadequate anesthesia. The current study was designed to determine whether the probability of memory declines with increasing depth of the hypnotic state.

Method: A list of words was played *via* headphones during surgery to patients who had suffered acute trauma. Several commonly used indicators of anesthetic effect, including the bispectral index, were recorded during word presentation. First, these indicators served as predictors of the memory performance in a postoperative word stem completion test. Second, general memory performance observed in the first part was separated into explicit and implicit memory using the process dissociation procedure, and then two models of memory were compared: One model assumed that the probability of explicit and implicit memory decreases with increasing depth of hypnotic state (individual differences model), whereas the other assumed equal memory performance for all patients regardless of their level of hypnotic state.

Results: General memory performance declined with decreasing bispectral index values. None of the other indicators of hypnotic state were related to general memory performance. Memory was still significant at bispectral index levels between 60 and 40. A comparison of the two models of memory resulted in a better fit of the individual differences model, thus providing evidence of a dependence of explicit and implicit memory on the hypnotic state. Quantification of explicit and implicit memory revealed a significant implicit but no reliable explicit memory performance.

Conclusions: This study clearly indicates that memory is related to the depth of hypnosis. The observed memory performance should be interpreted in terms of implicit memory. Auditory information processing occurred at bispectral index levels between 60 and 40. (Key words: Bispectral index; depth of anesthesia; information processing; word stem completion.)

This article is accompanied by an Editorial View. Please see: Veselis RA: Memory function during anesthesia. *ANESTHESIOLOGY* 1999; 90:648-50.

DURING the past 20 yr, considerable research has focused on memory during general anesthesia.¹⁻⁵ An important point of discussion in this field is whether memory of intraoperative events results entirely from moments of awareness. The aim of the current study was to show that explicit and implicit memory performance decreases as the depth of the hypnotic state increases. To establish reliable evidence of such a relation, it is necessary to examine a group of patients with considerable variation in the depth of the hypnotic state. We tried to meet this requirement by studying a large group of patients who had suffered injuries varying from minor to serious trauma. Recall has been reported to be as high as 43% in serious cases compared with 11% in less serious cases.⁶

Before we describe our study, it would be useful to clarify how the various terms concerning memory are used in this article. Because both explicit and implicit memory might contribute to what is commonly called memory, "general memory performance" is used when no effort is made to distinguish explicit from implicit memory. As an illustration of explicit and implicit memory, consider the memory test used in this study. We presented words during surgery to ensure that the postoperative word stem completion test (WS test) concerned the period during general anesthesia. Intraoperative presentation of, for example, the word *apply* was

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expected to result in higher hit rates of the response "apply" when patients completed the stem *app* than would be expected by base rate performance (*i.e.*, performance without previous presentation).⁷ Explicit memory is evident if patients recall the word *apply*. Higher hit rates in the WS test are referred to as implicit memory if and only if they occur without recalling the words presented during surgery. In the past, higher hit rates in the WS test often were ascribed exclusively to implicit memory, but if it is not ensured that there is no explicit memory, the observed effects might result from both types of memory; that is, they indicate general memory performance.^{7,8}

In the first part of this study, we wanted to determine whether general memory performance for words presented during surgery depends on the hypnotic state as measured by several indicators of anesthetic effect, including the bispectral index (BIS). In the second part, we addressed two questions: (1) whether general memory performance results from implicit or explicit memory, or both; and (2) whether both types of memory depend on the hypnotic state. For this purpose, the WS test was based on the process dissociation procedure (PDP).⁹⁻¹¹ The full PDP design consists of two parts. In the inclusion part, patients are asked to complete the stems (if possible) with a word presented during surgery, or, otherwise, with the first word that comes to mind. Because both explicit and implicit memory lead to the same response (*i.e.*, completion with the presented word), the inclusion part is a measure of general memory performance. To separate explicit and implicit memory, an exclusion part is necessary in which the patients are asked (if possible) not to use presented words for stem completion but to use any other word they could think of. Contrary to the inclusion part, explicit memory in the exclusion part results in hit rates lower than the base rate. A combination of the two parts of the test allows separate estimates of explicit and implicit memory to be calculated (appendix 1).

The PDP is used widely by psychologists in memory research¹²⁻¹⁴ and to some extent has been used to assess explicit and implicit memory during anesthesia.¹⁵ We used the full PDP design in combination with two different models of memory: (1) a model developed by Buchner *et al.*¹⁶ that assumes that participants do not differ in explicit and implicit memory performance, and (2) an extension of Buchner's model, the individual differences model (IDM), which allows patients who vary in depth of hypnotic state to differ also in both types of memory.¹⁷ If both explicit and implicit memory

decrease with increasing depth of the hypnotic state, the IDM should provide a better fit of the word stem completion data than would Buchner's model.

Methods

This study was approved by the human investigations committee of Emory University School of Medicine, Atlanta, Georgia. Because of the nature of trauma surgery, informed consent could not be obtained reliably before surgery and was obtained subsequently before memory testing. One hundred forty-five patients who had suffered acute trauma and were undergoing surgery at Grady Memorial Hospital were enrolled in the intraoperative part of the study. Trauma was defined as any physical wound or injury caused by an extrinsic agent, and thus included a wide variety of injuries ranging from minor trauma, such as cuts and simple gun shot wounds, to serious trauma with extensive blood loss. Consent could not be obtained from 49 patients for the following reasons: 13 patients died during or shortly after surgery, 12 patients could not be interviewed within 6 days after surgery because they were still intubated, 14 patients were excluded because anesthetics were administered other than those described by the standard anesthetic protocol (*e.g.*, benzodiazepines, scopolamine, or both), 4 patients were younger than 18 yr, and 6 patients did not wish to participate in the study. The 96 patients who completed the postoperative memory test spoke English as their first language and had no known hearing problems.

The 32 five-letter words used in this study were based on the results of a pilot word stem completion study performed in a comparable group of patients. This study established the rate of correct word stem completion without previous presentation of the corresponding word (*i.e.*, base rate completion). The selected 32 words had homogenous base rates of approximately 30% and were assigned randomly to one of four word lists. Each patient was presented two of the lists during surgery (16 target words) and was tested after recovery on all 32 words, thus including the two lists that had not been presented during operation (16 distractors). Furthermore, two word lists were used in the inclusion part of the memory test, and two were used in the exclusion part. The word lists were counterbalanced so that each of the 32 words appeared equally often as a target word and as a distractor in both the inclusion and exclusion parts (fig. 1).

	list 1 (words 1-8)	list 2 (words 9-16)	list 3 (words 17-24)	list 4 (words 25-32)
group 1	inclusion target	inclusion distractor	exclusion target	exclusion distractor
group 2	exclusion distractor	inclusion target	inclusion distractor	exclusion target
group 3	exclusion target	exclusion distractor	inclusion target	inclusion distractor
group 4	inclusion distractor	exclusion target	exclusion distractor	inclusion target

Fig. 1. Counterbalancing schema. During surgery, only two lists (target words) are presented. The postoperative memory test consists of all four lists (target and distractors; appendix 2). For example, if patients had been assigned randomly by the computer to group 3, they would have been presented lists 1 and 3 during surgery as target words, and they would have been tested on lists 3 and 4 in the inclusion part and on lists 1 and 2 in the exclusion part.

Electric activity of the brain was measured using an A1000 monitor (Aspect Medical Systems, Nattick, MA) using a two channel referential montage. When the patients arrived in the operating room, four self-prepping, low-impedance electrodes (Zipprep; Aspect Medical Systems) were attached to the following sites: channel 1 and 2 to the left and right outer malar bone (At1 and At2), the referential electrode high on the forehead (Fpz), and the ground electrode approximately 2 cm to the right edge of the reference electrode (Fp2). Impedance was kept below 5 k Ω by adjusting the electrodes if necessary. The following data were recorded automatically and continuously to a microcomputer: BIS, Median Frequency, Spectral Edge Frequency (every 15 s), mean arterial blood pressure and heart rate data (every 3 min), and end-tidal concentrations of anesthetic gases (every 10 min).

The anesthetic procedure was standardized and consisted of induction with etomidate and maintenance with isoflurane, fentanyl, and an air-oxygen mixture. Neuromuscular blockade was with succinylcholine and vecuronium or pancuronium. The administration of anesthesia (dosage, time of administration) and necessary deviations from the standard protocol were the anesthesiologist's responsibility, who was by no means influenced by the study. Patients who had received benzodiazepines or scopolamine were excluded from the study. All personnel were blinded to the BIS, spectral edge frequency, median frequency, and the word presentation.

The target words were presented *via* closed headphones connected to a Macintosh PowerBook 180 (Apple Computers, Cupertino, CA). The headphones were

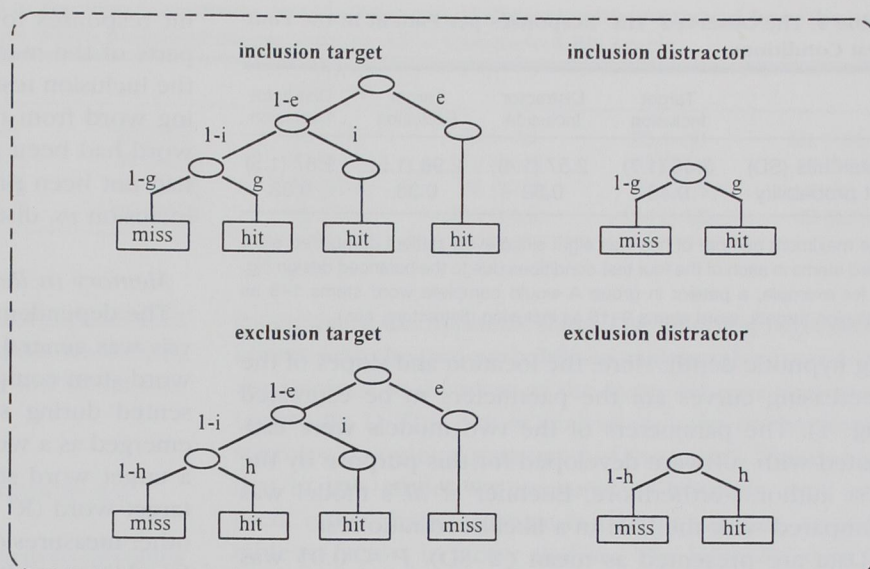
placed on each patient's ears, and the program for word presentation was started as soon as possible after induction with etomidate. The program chose the word lists corresponding to the counterbalancing scheme (*i.e.*, group membership of the patient; for an example, see the legend to figure 1) and presented the words in a random order that differed for each patient. Each of the 16 target words was repeated consecutively 40 times with a 2-s delay between repetitions. Therefore, the duration of presentation of each target word was approximately 3 min, with a 2-s interval between two different target words. Word presentation lasted 45 min in all. Because automatic data logging was used, each word presentation could be associated with a corresponding 3-min recording of electric activity of the brain and other variables. Consequently, the mean values of BIS and the other indicators of anesthetic effect for each presented word could be computed.

After operation, the patients were visited twice daily to ensure that the memory test was administered as soon as the patient was responding adequately according to the nurse in charge. The length of time interval between surgery and testing was recorded for each patient, and informed consent was then obtained. Using a structured interview, the patient was asked about recall of pre-, intra-, and postoperative events, and about his or her native language and any hearing problems. A computerized WS test was administered using the Macintosh PowerBook.

The WS test had three parts. The first part consisted of an exercise to familiarize the patient with the WS task. Then the inclusion and exclusion parts were administered. Based on the observed hit frequencies in the

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Fig. 2. Buchner *et al.*'s¹⁶ multinomial processing model of memory. The parameter e represents explicit memory, i represents implicit memory, and the parameters g and h are the base rate parameters in the inclusion and exclusion parts, respectively.



inclusion and exclusion parts, the probability of explicit and implicit memory could be calculated (appendix 1).

Before each part of the test, the test instructions were explained thoroughly. During the explanation, the instructions were visible to the patient on the computer screen. The instructions included an example for each part of the test. The word stems were presented in the same way as during surgery (*i.e.*, auditorily) because changes of modality might influence implicit memory.^{18,19} The digital sound sample of the word stem had been derived from the sound sample of the whole word used for presentation during surgery. The computer played the stem twice. To improve comprehension, the stem also was visible on the screen. The computer program for the WS test "recognized" the patients by their subject numbers, chose the relevant word lists for the inclusion and exclusion conditions, and presented the stems in a random order that differed for each patient. In both parts of the test, target words were mixed with distractors. The patients' responses were entered in the computer by the observer. As a measure of cued recall, the patients were asked to report during the WS test each word they could recall from the operation. To increase the patients' effort to recall presented words, they were asked again after each part of the test whether they could remember any of the words presented during surgery.

Data Analysis

The first part of the data analysis consisted of a logistic regression model with general memory performance as a

dependent variable. Therefore, this part of the analysis was based on the data obtained in the inclusion part of the WS test. During surgery, 768 inclusion target words had been presented (96 patients \times 8 words; fig. 1). The means of BIS, median frequency, spectral edge frequency, and the other indicators by hypnotic state (heart rate, mean arterial pressure, end-tidal gas concentrations) were calculated for each of the 768 presented words. General memory performance (*i.e.*, whether the corresponding stem was completed with the word presented during surgery, hit or miss, respectively) was entered as a dependent variable in a logistic regression using the indicators of hypnotic state as predictors. In this way, general memory performance was related to the hypnotic state during the 3-min interval in which a certain word had been presented. This analysis was not conducted for each patient separately but related the responses on all 768 inclusion word stems (96 patients, 8 inclusion word stems) to the hypnotic state during the presentation of the corresponding words. Therefore, this part of the data analysis captured fluctuations in hypnotic state within and between patients.

In the second part, the two models were evaluated. Buchner *et al.*'s¹⁶ model assumes that explicit and implicit memory have the same probability in all patients regardless of their hypnotic state. Therefore, in this model the probabilities of explicit and implicit memory have the same value for all patients, which means that apart from the base rate, two parameters need to be estimated: parameters e and i as shown in figure 2. The IDM allows both probabilities to decrease with increas-

Table 1. The Observed "Hit" Responses per Patient in the Four Test Conditions

	Target Inclusion	Distractor Inclusion	Target Exclusion	Distractor Exclusion
Mean hits (SD)	3.46 (1.7)	2.57 (1.4)	2.98 (1.5)	2.67 (1.5)
Hit probability	0.43	0.32	0.38	0.33

The maximum number of hits was eight since every patient completed eight word stems in each of the four test conditions due to the balanced design (fig. 1, for example, a patient in group A would complete word stems 1–8 as inclusion targets, word stems 9–16 as inclusion distractors, etc.).

ing hypnotic depth. Here, the location and slopes of the decreasing curves are the parameters to be estimated (fig. 4). The parameters of the two models were estimated with software developed for this purpose by the first author. Furthermore, Buchner *et al.*'s model was compared with the IDM in a likelihood ratio test.

Data are presented as mean (\pm SD). $P < 0.05$ was considered significant.

Results

The patients' ages were 31 ± 10 yr (range, 18–64 yr). Eighty-two men and 14 women participated in the memory test. The duration of surgery was 3 ± 2 h (range, 1–10 h), and the interval between the operation and the memory test was 42 ± 31 h (range, 6–143 h). The mean BIS was 54 ± 14 (range, 21–96). Heart rate was 86 ± 20 beats/min, mean arterial pressure was 85 ± 21 mmHg, and the end-tidal isoflurane concentration was $1 \pm 0.5\%$.

During the memory test, the word stems on the screen of the laptop computer served as cues for recall (cued recall test). During surgery, 1,536 words had been presented (each of the 96 patient had been presented with 8 words for the inclusion part and an equal number of target words for the exclusion part of the memory test). Twenty-two patients reported to have recalled one or more words from the intraoperative presentation, resulting in 43 recollected words. Six words were recalled correctly, compared with 37 false alarms.

All 96 patients completed the structured interview (self-report of recall). One patient claimed to have heard voices during surgery. This patient had had no anesthetic agent for a period of approximately 5 min. He could not recall any of the words presented during surgery nor did his response pattern in the WS test indicate explicit or implicit memory.

Evidence of Auditory Information Processing

Word completion with one of the 32 study words was called a "hit." Table 1 shows the means of the observed

hit responses for target words and distractors in both parts of the memory test. Patients completed stems in the inclusion test significantly more often with a matching word from the set of 32 words when the relevant word had been presented during surgery than when it had not been presented (paired Student's *t* test, target inclusion *vs.* distractors inclusion; $P < 0.001$).

Memory in Relation to Hypnotic State

The dependent variable in the logistic regression analysis was general memory performance, as measured by word stem completion with inclusion target words presented during surgery (*i.e.*, hits *vs.* misses). The BIS emerged as a weak but significant predictor of whether a target word stem was completed with the matching target word ($R^2 = 0.12$). The regression weights of all other measures of anesthetic effect were not significant. In addition, neither the time interval between surgery and memory test nor the duration of surgery were significantly related to word stem completion.

In *post hoc* chi-square analyses, two questions were addressed: (1) Is general memory performance as measured by hit frequency still significant at BIS levels assumed to indicate adequate anesthesia (*i.e.*, BIS values < 60), and (2) Is general memory performance significant even below BIS values of 40. For this purpose, BIS levels were categorized. Table 2 shows the number of presented target words for each category. Hit frequencies of target words were computed for each BIS category. By definition, distractors were not presented during surgery and therefore had no corresponding BIS value. For all BIS categories, matching distractor frequencies were calculated from base rate performance (table 1, distractor inclusion probability) and several observations equaling the number of target words in the corresponding BIS category (fig. 3). Based on table 2, chi-square analyses (hits/misses *vs.* target/distractor) could be computed for BIS < 60.1 and for BIS < 40.1 . General memory performance increased with increasing BIS values and was higher than base rate performance at BIS values less than 60.1 ($\chi^2 = 8.63$, $df = 1$). At BIS values less than 40.1, general memory performance did not differ significantly from base rate performance ($\chi^2 = 0.61$, $df = 1$).

To evaluate the validity of averaging BIS values over each 3-min interval of word presentation, we compared hit rates for BIS values between 40 and 60 based on mean BIS values to hit rates on the maximum BIS in the 3-min interval. In a random subsample of 200 presented words (*i.e.*, 26% of all target words), 95 words were categorized between BIS 40 and 60 based on mean BIS

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Table 2. Number (%) of Target Hits Observed in the Stem Completion Test, Number (%) of Distractor Hits Estimated from the Observed Base Rate, and Number (%) of Target Words Presented during Surgery, All at Categorized BIS Levels

	BIS Level						
	20-30	30.1-40	40.1-50	50.1-60	60.1-70	70.1-80	80.1-96.5
Target hits	7 (38.9)	41 (36.3)	82 (40.6)	81 (44.5)	52 (46.9)	57 (50.0)	19 (67.9)
Distractor hits	6 (33.3)	36 (31.9)	65 (32.2)	59 (32.4)	36 (32.4)	37 (32.5)	9 (32.1)
Presented targets	18 (2.3)	113 (14.7)	202 (26.3)	182 (23.7)	111 (14.5)	114 (14.8)	28 (3.7)

with a hit rate of 41.05% (*i.e.*, 39 hits). Categorization of the same 200 words based on maximum BIS resulted in 81 words between BIS 40 and 60 with a 40.74% hit rate (*i.e.*, 33 hits).

Explicit and Implicit Memory in Relation to the Depth of Hypnotic State

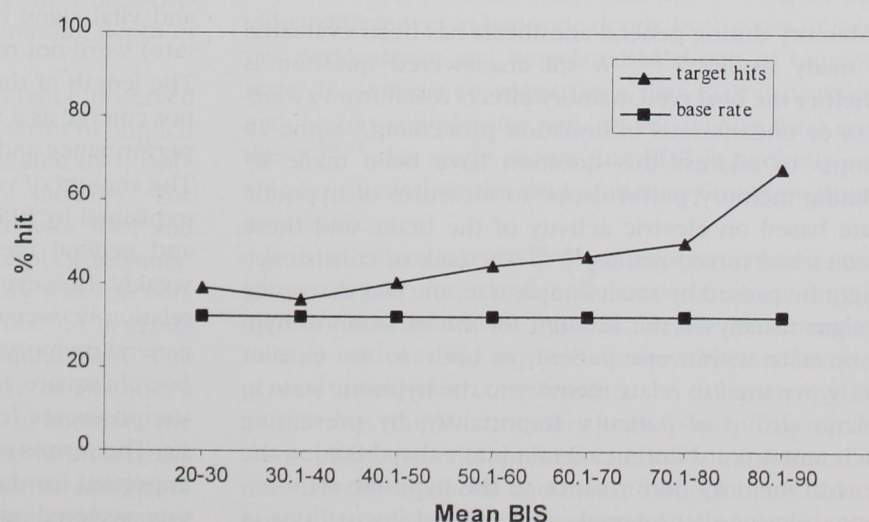
Buchner's Model. This part of the analysis involves estimation of the model parameters for explicit memory (*e*) and implicit (*i*), as shown in figure 2. Parameter values are computed that are most likely given the observed hit frequencies. Such estimates are called "maximum likelihood estimates."²⁰ The maximum likelihood estimate for explicit memory was $e = 0.057$ (SE = 0.033) and $i = 0.102$ (SE = 0.026) for implicit memory. The lower bound of the 95% confidence interval for parameter *e* ($1b_e$) was -0.008 ; the upper bound (ub_e) was 0.122. Because zero is an element of this interval, the estimate for *e* does not differ reliably from zero. The estimate for implicit memory *i* differs reliably from zero with $1b_i = 0.051$ and $ub_i = 0.153$.

Individual Differences Model. Explicit and implicit memory performances were modeled as probability

functions of the hypnotic state. The resulting regression curves with the two probabilities as dependent variables are assumed to decrease as the hypnotic state increases (appendix 1). This part of analysis includes the hypnotic state as a theoretical parameter of the model. This means that in this model no measures of hypnotic state are used; rather, hypnotic state is a latent variable, comparable to factors in factor analysis. The hypnotic state is expressed in units of standard deviations from the mean, which is set to zero. Thus, positive values indicate a lighter than average hypnotic depth, whereas negative values indicate lower than average hypnotic depth. Figure 4 shows the estimated curves. The localization parameters for the explicit and implicit memory curves (*i.e.*, the value of the hypnotic state for which the probability of explicit or implicit memory equals 0.5) were estimated to be 3.26 (0.80) and 1.81 (0.31) standard deviations (SEM), respectively.

Comparing Models. The model fit of IDM and the Buchner model were compared in a likelihood ratio test. This test determines whether the introduction of an extra parameter for individual differences in hypnotic state, as is done in IDM, leads to a significantly better fit

Fig. 3. Increase of target hit rates compared with base rate performance at categorized bispectral index values.



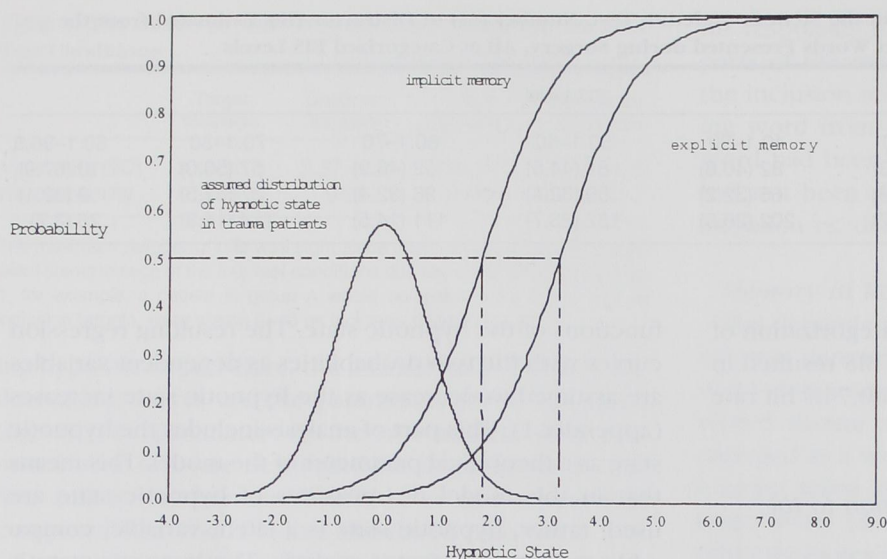


Fig. 4. The individual differences model assumed a bell-shaped distribution of the 96 trauma patients with respect to hypnotic state and explicit and implicit memory performance as a function of hypnotic state. Hypnotic state is an unmeasured, theoretical variable of the individual differences model. The mean and standard deviation of the distribution of hypnotic state are set to zero and one, respectively. Thus, the scale of hypnotic state is in standard deviations from the mean of the distribution of trauma patients.

of the data than would a model without such a parameter. The likelihood ratio statistic (R) is approximately chi-square distributed with the degrees of freedom equaling the number of extra parameters (*i.e.*, $df = 1$ in this study).²¹ The IDM provided a better description of the data than did the Buchner model: The likelihood ratio statistic was $R = 13.79$. Assuming a chi-square distribution for R with one degree of freedom, the increase in model fit by allowing for individual differences in explicit and implicit memory was significant ($P < 0.01$).

Discussion

Memory during general anesthesia has been evaluated in many studies.^{1,22,23} A still-unanswered question is whether the observed memory effects result from awareness or unconscious information processing.³ Some attempts to address this question have been made by relating memory performance to measures of hypnotic state based on electric activity of the brain, and these studies had mixed results.²⁴⁻²⁸ The lack of consistency might be caused by small sample size, the fact that study designs usually do not account for the variation of hypnotic state within one patient, or both. In the current study, we tried to relate memory to the hypnotic state in a large group of patients. Importantly, by presenting each target word during a 3-min interval and linking the general memory performance to the hypnotic state observed during that interval, we captured fluctuations in

hypnotic state within and between patients. Data analysis consisted of two separate approaches: (1) Completion of a particular word stem (hit/miss) was regressed on the mean values of the indicators of anesthetic adequacy observed during the intraoperative presentation of the corresponding word, and (2) the explicit and implicit contributions to stem completion were separated according to the PDP, and two models of memory were compared; one allowed patients with different depths of hypnotic state to vary in explicit and implicit memory performance, whereas the other did not.^{9,16,17}

In the regression model, only BIS emerged as a significant predictor of general memory performance. Median frequency, spectral edge, end-tidal gas concentrations, and vital signs variables (mean arterial pressure, heart rate) were not related to general memory performance. The length of the time between surgery and testing did not emerge as a significant predictor of general memory performance and therefore did not confound the results. The amount of variance in general memory performance explained by BIS ($R^2 = 0.12$) seems to indicate that BIS and general memory performance were related only weakly. However, more convincing evidence favoring a relation between hypnotic state as measured by BIS and general memory performance was provided by the *post hoc* chi-square analyses, whose underlying statistical assumptions are less restrictive than the regression analysis. The results of the chi-square analyses might be more important for the following reason. The regression analysis assumed word stem completion to be a logistic

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function of BIS, whereas the chi-square analysis did not imply any restrictions on this relation. The frequency of word stems completed with words presented during surgery was higher in the higher BIS categories compared with the lower categories. The weak relation between hypnotic state and general memory performance in the regression analysis might, therefore, be due to the restriction of a logistic function and not to a weak relation *per se*. The chi-square analyses confirmed that general memory performance was still significant at BIS values considered to indicate adequate anesthesia (*i.e.*, between 60 and 40). It might be argued that using the mean BIS during the 3-min intervals of word presentation obscures peaks of lighter hypnotic state during which the patient might have consciously perceived the words, thus leading to an overestimation of general memory performance at BIS values less than 60. However, *post hoc* comparison of hit rates calculated for mean BIS and hit rates based on maximum BIS did not support this argument: The pattern of results was unchanged.

Further evidence in favor of a relation between hypnotic state and memory was established in the second part of the study. Here, we tried to determine whether explicit and implicit memory decreased with increasing hypnotic depth, and we quantified explicit and implicit contributions to general memory performance. Model comparison resulted in a better fit of IDM, which assumes that explicit and implicit memory decline with increasing hypnotic state, compared with Buchner's model, which assumes the same memory performance for all patients regardless of their hypnotic state. This finding is consistent with the results of the first part of the study and emphasizes that memory for words presented during surgery declines with increasing depth of the hypnotic state.

Whether the general memory performance observed in the first part should be interpreted in terms of implicit or explicit memory (or both) was addressed by quantifying the probability of both types of memory. The analysis based on PDP in combination with IDM and Buchner's model revealed evidence of implicit memory. Surprisingly, evidence of explicit memory was less conclusive, particularly when considering that no benzodiazepines or scopolamine had been administered. The parameter estimate for explicit memory of Buchner's model did not differ reliably from zero. In addition, the estimated explicit memory curve of the IDM indicated a low probability of explicit memory in this sample of trauma patients. The lack of convincing evidence of

explicit memory is consistent with the finding that only 6 of 1,536 words presented during surgery were correctly recalled, compared with 37 false alarms. Even if the presented words lack salience for the patients, the number of correctly recalled words is low. Furthermore, during the interview, which was done before the memory test, only one patient claimed to remember hearing voices from the intraoperative period.²⁹ His response pattern in the WS test did not indicate explicit or implicit memory. Thus, the general memory performance observed in the first part of this study should be interpreted in terms of implicit memory.

The lack of convincing evidence of explicit memory is not consistent with the results of an earlier trauma study by Bogetz and Katz,⁶ in which the incidence of recall had been observed to be as great as 43% in patients who suffered serious trauma. A reason for this might be a substantial improvement of the resuscitation of the patient in the field since Bogetz and Katz did their research in 1984, resulting in an increased tolerance for administration of anesthetic agents. Thus, more patients might have been anesthetized adequately in the current investigation compared with the earlier trauma study. This is supported by the fact that the mean BIS calculated for all of our patients was within the range that is assumed to represent adequate anesthesia (*i.e.*, BIS 54). In addition, the previous trauma study used open-ended questions to detect recall. In the current study, we showed that there is a substantial number of incorrectly recalled words. To ensure reliability, it seems preferable to use PDP, which does not rely on patients' self reports. In addition, PDP combined with IDM allows us to compute estimates for explicit and implicit memory; and, by allowing for individual differences in hypnotic depth, both types of memory performance can be related to depth of hypnotic state. In contrast to suggestions that PDP instructions may be too complex for patients recovering from anesthesia,^{30,31} this study shows that PDP is perfectly suitable for research in the field of memory function during anesthesia.

In conclusion, in a group of patients undergoing emergency surgery for trauma, the occurrence of implicit memory was related to hypnotic depth. We found no reliable evidence for explicit memory. Even at levels of general anesthesia considered to be adequate by BIS monitoring, implicit memory was found. This clearly shows that patients process auditory information at these levels of general anesthesia without being able to access consciously the information after recovery.

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Appendix 1: Methods

Process Dissociation Procedure

The process dissociation procedure was developed to separate explicit and implicit memory within one test.⁹⁻¹¹ The memory test consists of two parts. The essential feature of the procedure is that in the inclusion part, explicit and implicit memory will lead to identical responses, whereas in the exclusion part the two types of memory performance will have an opposite effect, thus leading to different responses.

After the presentation of a list of words (*i.e.*, target words) during surgery, in both parts of the word stem completion test patients is instructed to regard the word stem as a help (or cue) to recall the target word. Suppose the word *apply* had been on the presented list. The participant is shown the stem *app* and asked to look at that stem to remember the target word *apply*. In the inclusion part, the stem should be completed with the recalled target word (*i.e.*, *apply*), whereas in the exclusion part stems should not be completed with the recalled target word. Rather, participants are asked to generate other solutions to complete the presented word stem (*i.e.*, a new word such as *apple* or *approach*). Consequently, explicit memory (*i.e.*, recall) leads to different responses in the two parts of the test. In other words, implicit memory effects in the absence of recall should in both parts of the test increase the percentage of target words during testing. Explicit memory, on the contrary, should enhance performance only the inclusion part. In the exclusion part, a hit rate less than the base rate should be observed.

In both parts, target word stems are mixed with distractor stems (*i.e.*, stems of words that were not presented during surgery). Balancing target words and distractors allows base rate performance to be calculated (*e.g.*, completion of the stem *app* with the word *apply* without previous presentation of *apply*).

Buchner, Erdfelder, and Vaderrodt-Plunneke's Multinomial Processing Model of Memory

Buchner *et al.*¹⁶ describe the response behavior in the process dissociation procedure in terms of multinomial processing trees (fig. 2). According to this model, responses in a word stem completion test are determined by a (series of successive) step(s). The parameters of this model are interpreted in terms of probabilities.

The first step in both the inclusion and exclusion target trees depends on explicit memory; that is, whether a word is recalled (*i.e.*, parameters e and $1-e$). The next step in Buchner *et al.*'s processing model refers to implicit memory. Because explicit memory is generally assumed to overrule implicit memory effects, the latter can be only observed if the patient has no explicit memory of the target word. The parameter for this level is i . In case there is neither explicit nor implicit memory for a presented word, the response in the word stem completion test is assumed to depend on guessing. The corresponding parameters are g and b for the inclusion and exclusion parts, respectively. The parameters of the processing trees for target words in Buchner *et al.*'s model are identical in the inclusion and exclusion conditions. Be-

cause of the different test instructions, the response patterns differ in one branch: For inclusion target words, the branch with probability e leads to word stem completion with target words (hits), whereas in the exclusion condition this branch leads to completion with new words (misses). Therefore, the parameters e and i can be estimated.

Individual Differences Model

The individual differences model (IDM) is an extension of Buchner *et al.*'s¹⁶ multinomial model that allows for differences between patients. In IDM, the probability of explicit memory and the probability of implicit memory (parameters e and i of figure 2) as measured by hit or miss responses in the word stem completion test are both formulated as dependent variables of the independent variable hypnotic state. It is assumed that the probability of implicit and explicit memory increase with decreasing hypnotic depth. Because probabilities must remain between one and zero, the regression curves are assumed to be logistic. As stated earlier, in IDM the hypnotic state is a latent variable, which means that it is not necessary to measure hypnotic state to use this model: The regression curves are estimated based on the responses in the WS test using techniques developed in modern test theory.³²

Our interest here is the probability of explicit and implicit memory for patients with levels of hypnotic state that vary from "deep" *via* "average" to "light" levels of hypnotic state. This is accomplished by arbitrarily fixing the mean of the distribution of our latent variable "hypnotic depth" to zero. The standard deviation is set to one, thus establishing a scale for "hypnotic depth." Based on the responses of the patients, it is possible to calculate the most likely values for the slope and the localization of the curves with respect to the fixed distribution of hypnotic state. Suppose most patients complete most inclusion word stems with words presented during surgery and most exclusion stems with other words. This would be an indication that the average patient has explicit memory. In this case, the curve for explicit memory would be localized around the mean of the distribution. If, however, most of the patients could not include presented words in the inclusion part or exclude them in the exclusion part, the curve would be located to the right side of the distribution, thus indicating a low probability of explicit memory for most patients. The estimation of the localization and slope parameters involves an iterative optimization procedure in which the most likely values for the slope and localization parameters are estimated given the responses of the patients in the WS test. This way of modeling is a practical application of modern test theory.³²

The localization of the curves is determined by the breakpoint of each curve and is given in standard deviations from the mean. The breakpoints are (by definition) localized at the value of hypnotic state for which the probability of the corresponding type of memory is 0.5. In our case, the localization parameter (*i.e.*, the breakpoint) for implicit memory was 1.81 standard deviations, meaning that a patient had to have a rather light hypnotic state to have a 0.5 probability of implicit memory. If, for example, the localization parameter of the function for implicit memory had been estimated as zero, the result would suggest that the probability of implicit memory is 0.5 for patients with precisely the mean level of hypnotic state. If the localization parameter had been estimated to be less than zero, it would mean that the probability is 0.5 at levels of hypnotic state deeper than average. Because the localization parameter for explicit memory was 3.26

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standard deviations, we can conclude that the probability of explicit memory was extremely low in our sample: A patient had to have a light level of hypnotic state (*i.e.*, far to the right of the mean) to have a probability of approximately 0.1 of explicit memory (compare figure 4).

Appendix 2: Word Lists

List 1

1. marks
2. rinse
3. cloth
4. frame
5. mates
6. spell
7. store
8. seals

List 2

9. loads
10. thumb
11. glows
12. angle
13. shoes
14. coats
15. sales
16. limit

List 3

17. shine
18. bands
19. scope
20. pines
21. click
22. blown
23. fancy
24. crude

List 4

25. couch
26. skill
27. knock
28. bonus
29. trial
30. drums
31. scare
32. pairs

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